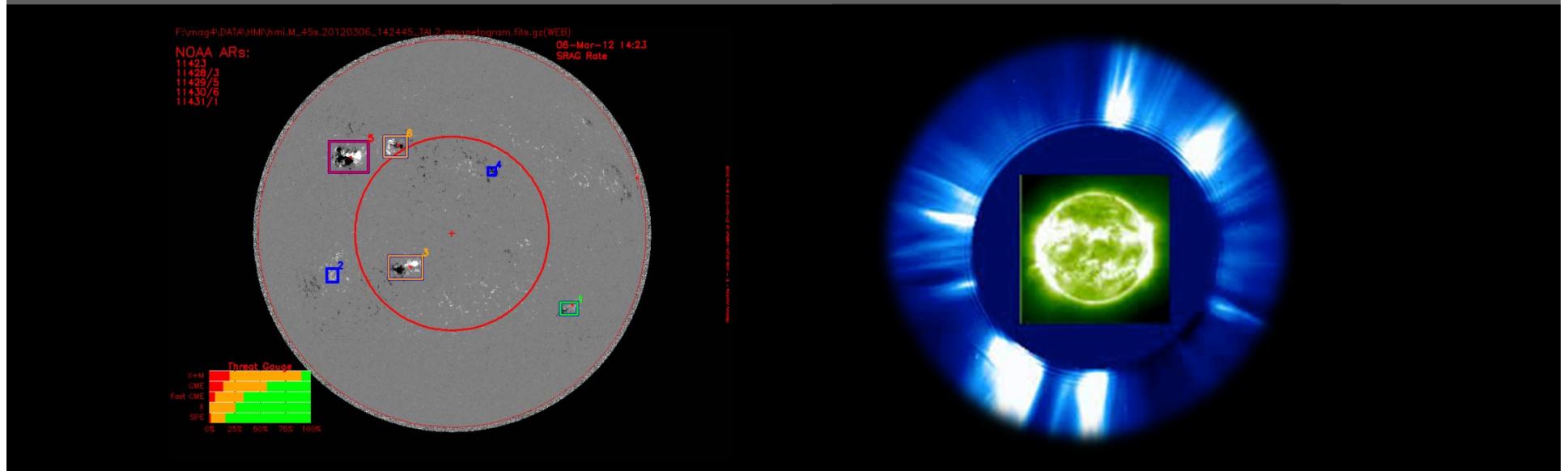




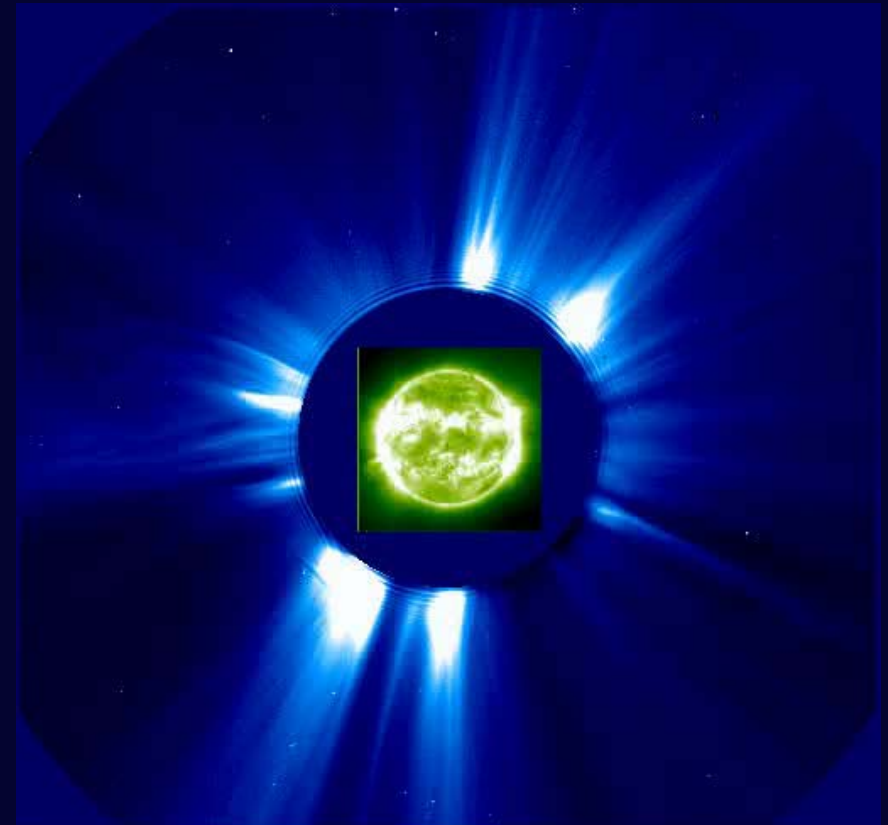
## SCIENCE & TECHNOLOGY OFFICE



# How MAG4 Improves Space Weather Forecasting

David Falconer  
Igor Khazanov  
Nasser Barghouty

1. Space Weather Background
2. MAG4 (Magnetogram Forecast)
  - a. What it is
  - b. Brief Background
  - c. History of R2O
3. MAG4 Automatic Process
4. Demo by Igor Khazanov
5. Improvements in the Pipeline
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  - b. Vector Magnetograms
6. How Effective
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  - b. 2x2 Contingence Table Metrics
7. Suggested Collaborations with AFWA

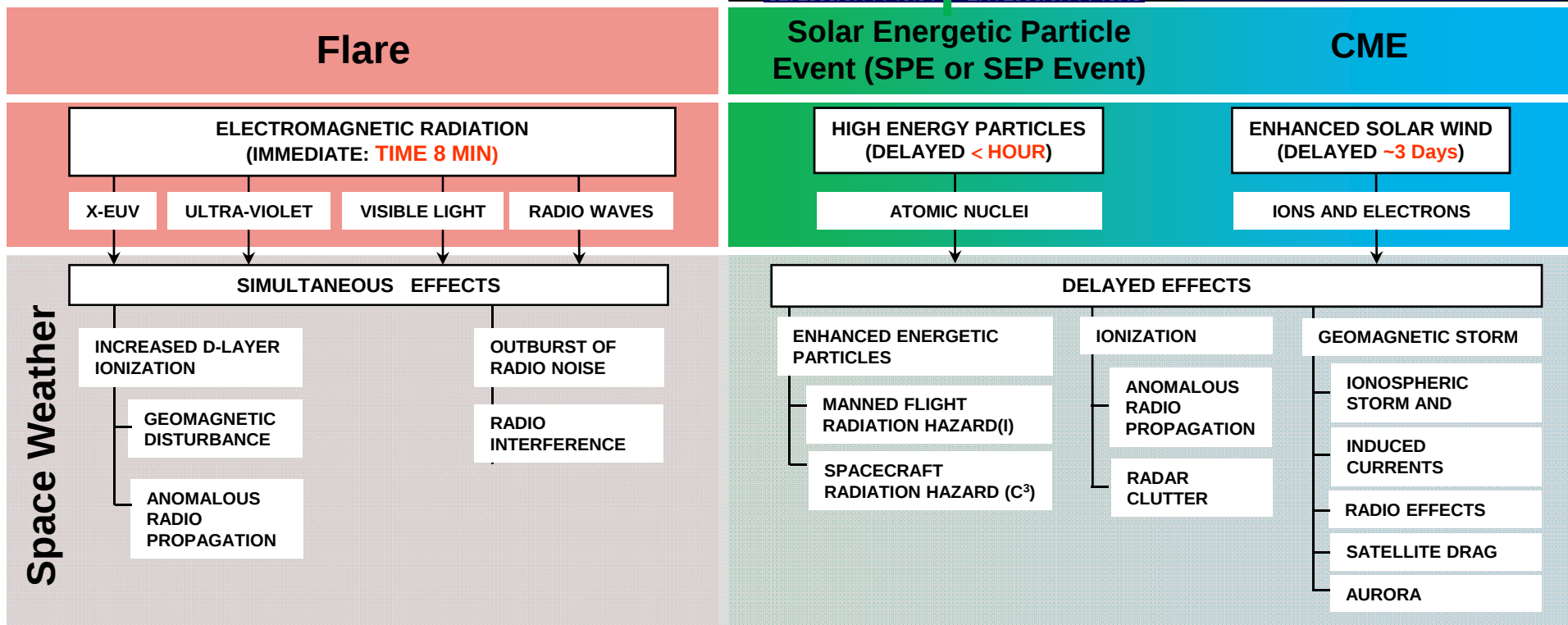
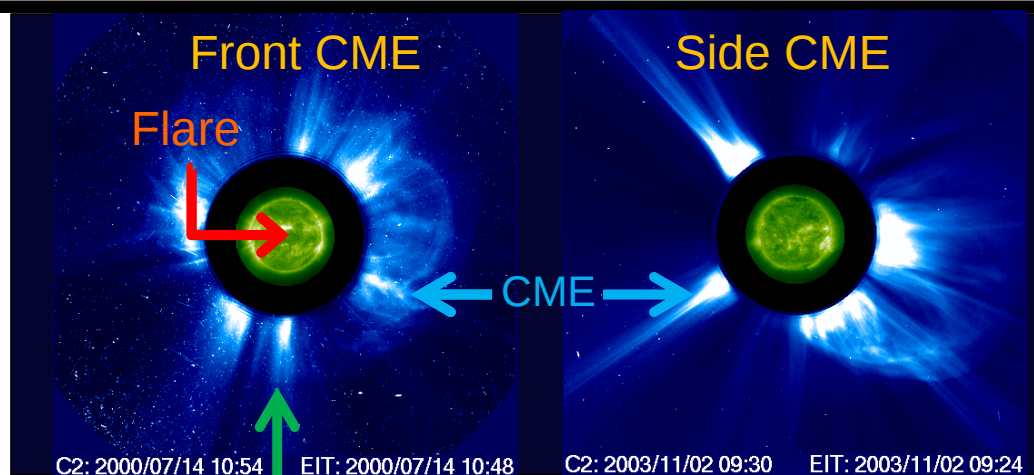


C2: 2000/07/14 09:30:05 EIT: 07/14 09:24:10

*Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event*

Dangerous space weather is driven by solar flares and Coronal Mass Ejection (CMEs).

Forecasting flares and CMEs is the first step to forecasting either dangerous space weather or All Clear.



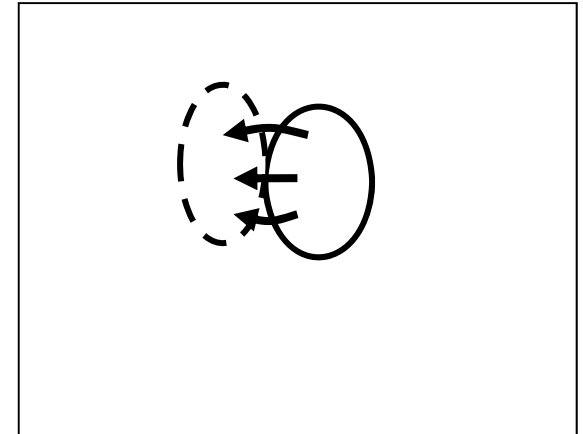
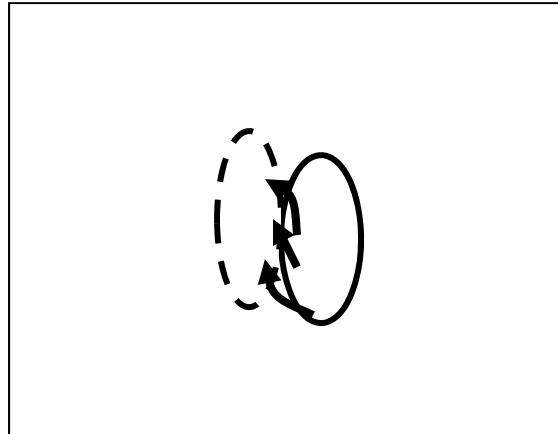
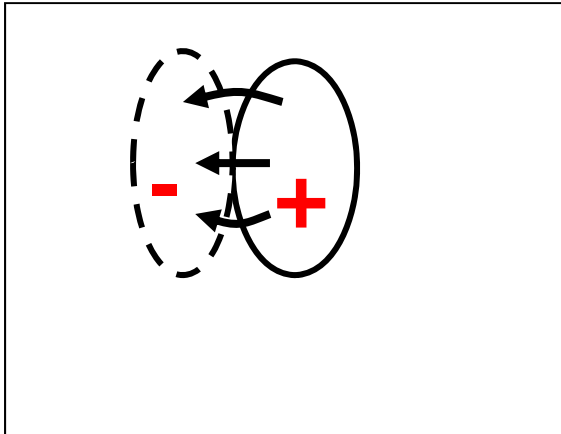
- MAG4 (Magnetogram Forecast), developed originally for NASA/SRAG (Space Radiation Analysis Group), is an automated program that analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and automatically converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events.
- MAG4 does not forecast a flare will occur at 12:02 tomorrow, but the probability of one occurring tomorrow.
- GONG ([Global Oscillations Network Group](#)) magnetograms, can be used instead as a **backup** but at a lower forecast accuracy.
- Present cadence of new forecasts: **96 minutes**.  
Vector magnetogram actual cadence: **12 minutes**.

- Flares and CMEs are known to be drivers of the most severe space weather
- Flares and CMEs typically originate in active regions (aka sunspots)
- Flares and CMEs are examples of exceptionally large explosive releases of magnetic energy stored in the corona
- While the amount of free energy cannot be measured directly, free-energy proxies can be measured
- Event rates have been shown to be correlated with values of free-energy proxies

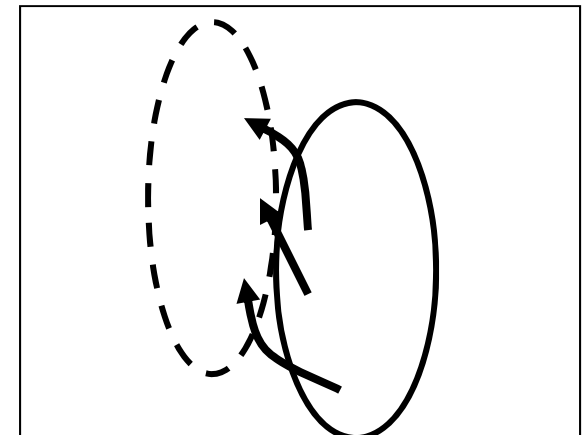
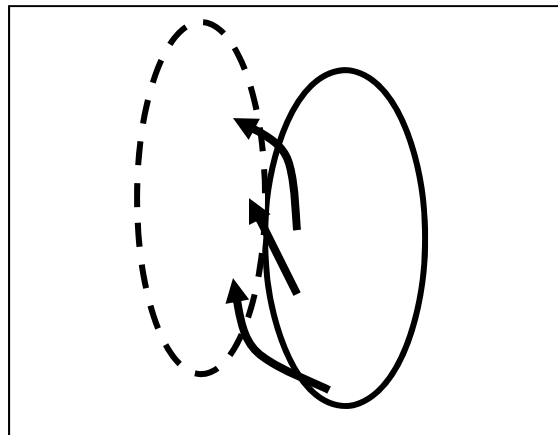
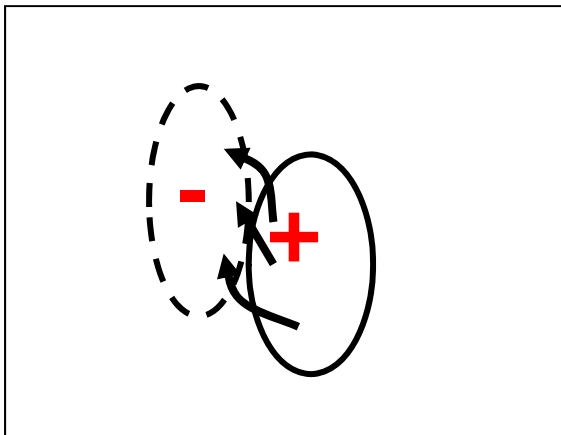
Contours Vertical Magnetic Field  
Arrows Transverse Magnetic Field

Currents  $\sim 10^{12}$  Amps

Less



More



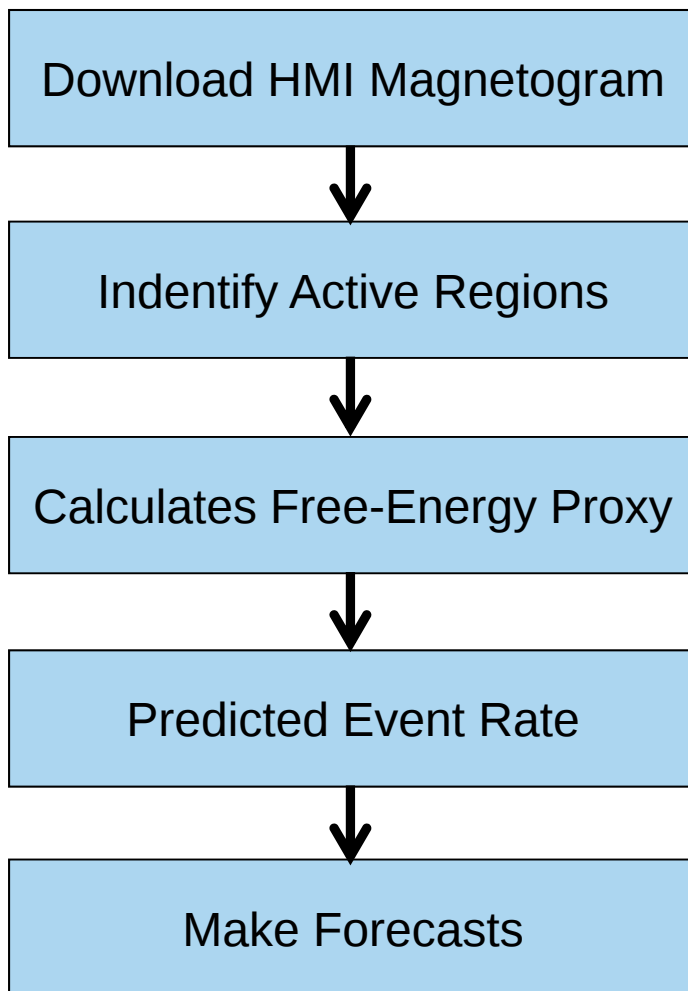
Twist

Size

**Free Magnetic  
Energy**



- **1973** The MSFC (Marshall Space Flight Center) Vector Magnetograph was made to support Skylab.
- **2000-present** MSFC analyzed vector magnetograms to study CME correlation with free-energy proxy.
- **2007-12** Co-I in a Multidisciplinary University Research Initiative/Neutral Atmosphere Density Interdisciplinary Research
- **2008** Partnered with SRAG (Space Radiation Analysis Group) and won an R20 NASA/Technical Excellence Initiative grant: Began building a database that grew to ~40,000 magnetograms of ~1,300 active region, covering years 1996-2004 with event catalog from SOHO/MDI (Solar and Heliospheric Observatory/Michelson Doppler Imager) observations.
- **2010-present** NASA's HEOMD (Human Exploration and Operations Mission Directorate) support.
- **2010** SDO is launched began transitioning from MDI to HMI line-of-sight magnetograms.
- **2011** **MAG4 installed at SRAG a NRT (Near-Real-Time) forecasting tool, and SRAG began pre-operations testing.**
- **2012** Provided NOAA web access to MAG4 NRT forecasts.
- **2013** Improve MAG4 so that it can use a combination of **free-energy proxy** and previous **flare activity**.
- **2013** Transition to HMI line-of-sight to vector magnetograms.



MAG4 is completely automated, from downloading magnetograms to outputting forecast products.



## Process 1: Identifying Active Regions



- Magnetograms are spatial maps of the magnetic field strengths.
- They come in two basic types
  - line-of-sight (right)
  - vector magnetograms
- Free-energy proxies can be measured for Active Regions (areas with sunspots) from either type of magnetogram.
- Line-of-sight magnetograms suffer reduced accuracy further from disk center.

Introduce Magnetogram,  
identify ARs.

NOAA ARs  
11423  
11426/3  
11429/5  
11430/6  
11431/1

06-Mar-2012 14:23

Best  
Accuracy

NOAA  
Active  
Regions  
(ARs)

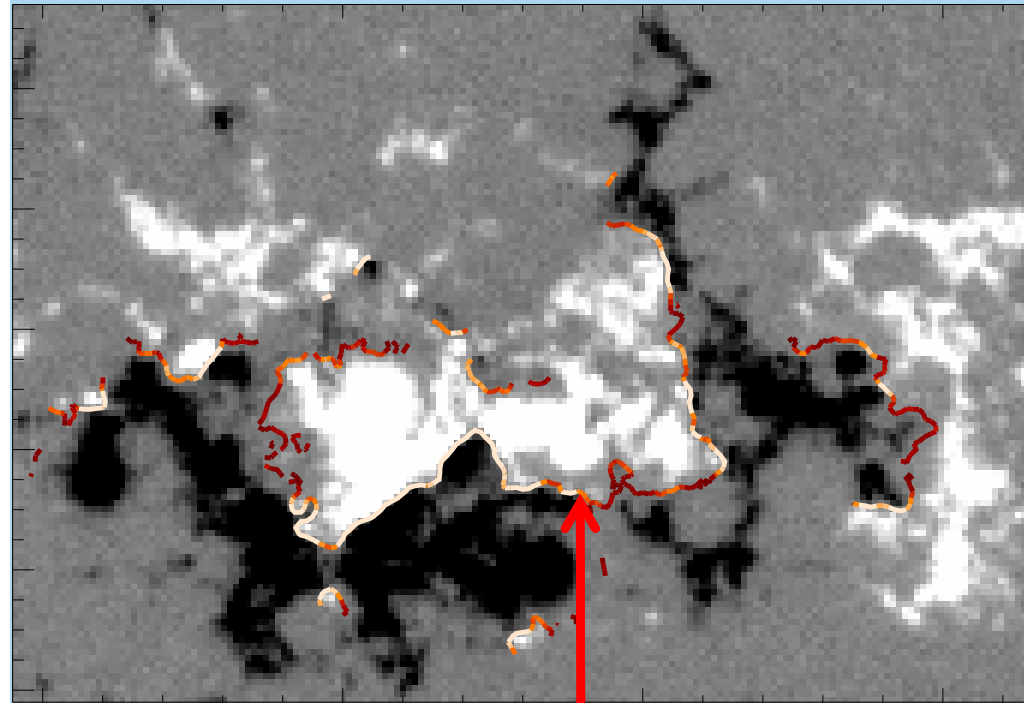
*A full-disk line-of-sight magnetogram of  
the Sun, from SDO/HMI.*

## Process 2: Calculating the Free-Energy Proxy



- Where the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field
- For **each Active Region**:  
The integral of the gradient along the neutral line is the free-energy proxy

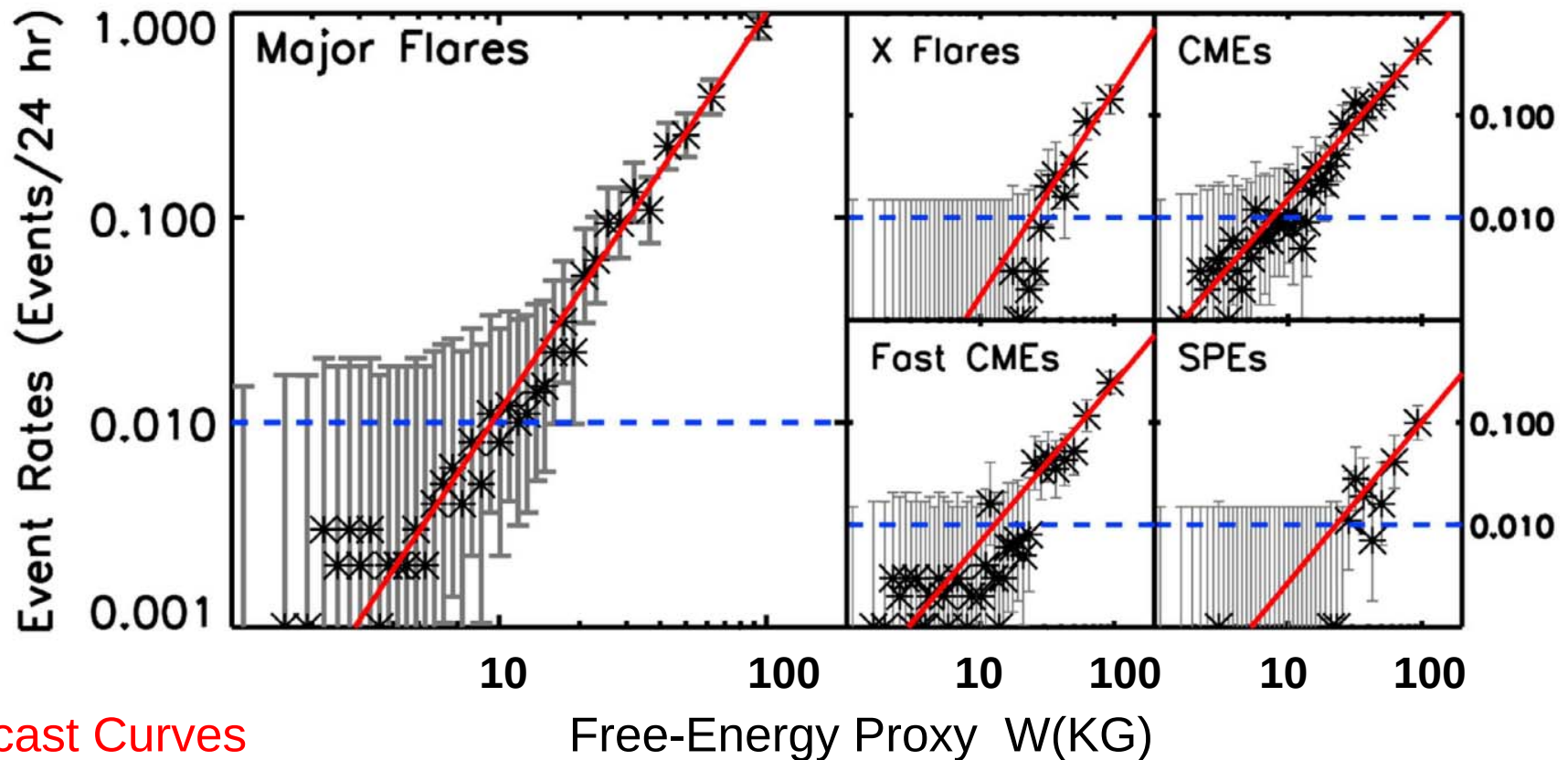
### A magnetogram of an active region



Neutral Line, color coded for gradient



## Process 3: Converting Free-Energy Proxy to Predicted Event Rates



These empirical forecast curves are used to convert our free-energy proxy into predicted event rates. Curves are derived from a sample of 40,000 magnetograms, from 1300 active regions observed between 1996-2004.

## Process 4: Forecast

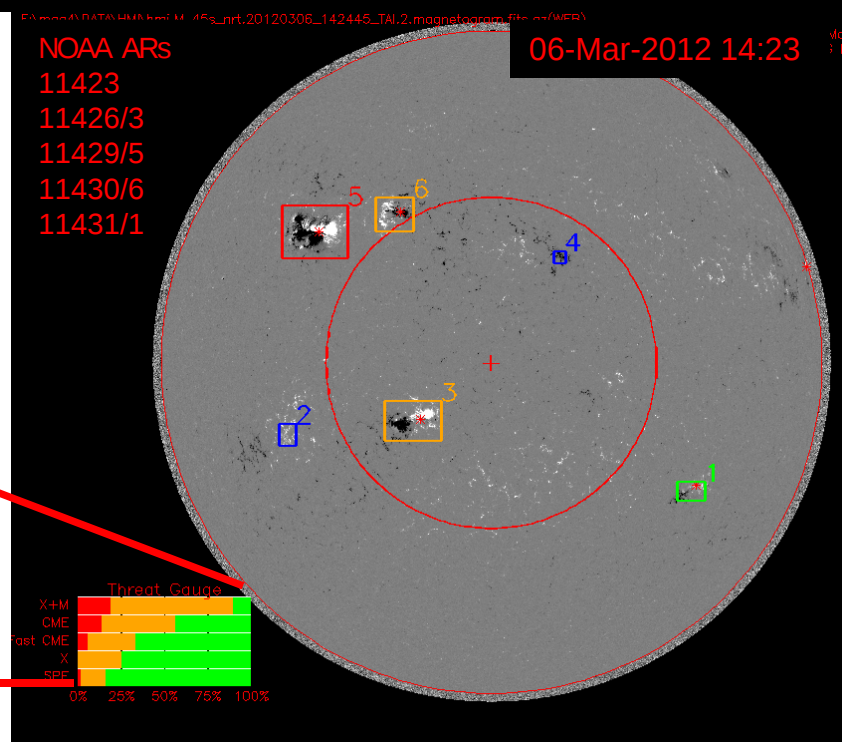
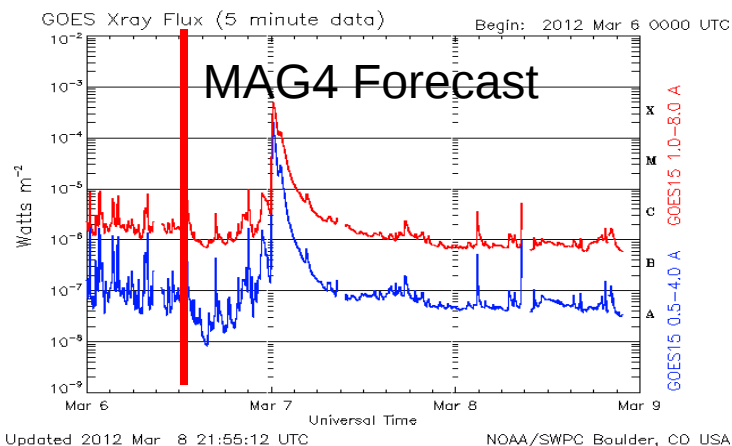
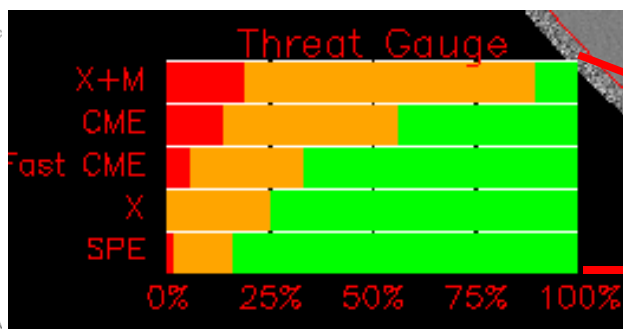
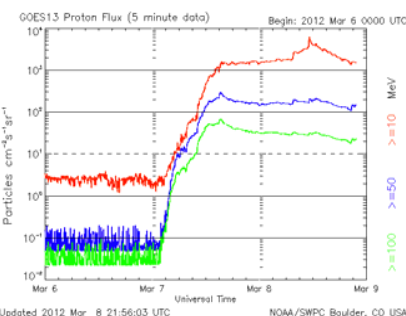
lots of layers on this page – not sure what you wanted showing



### Multiplicative uncertainty example

| Rate       | 1 sigma        | Probability |
|------------|----------------|-------------|
| Events/day | 66% Confidence |             |
| 0.02       | 0.01-0.05      | 0.7-5%      |
| 0.7        | 0.3-1.9        | 20-80%      |

For a Multiplicative Uncertainty of 2.7x



2012/03/06 14:23

| # | AR#   | WL!DSG!N | Lng  | Lat   |
|---|-------|----------|------|-------|
|   |       |          | (kG) | (deg) |
| 3 | 11428 | 9        | -21  | -17   |
| 5 | 11429 | 65       | -41  | 17    |
| 6 | 11430 | 11       | -25  | 20    |
| 1 | 11431 | 1        | 36   | -27   |

Disk Forecast Rates  
Multiplicative Uncertainties  
Disk All-Clear Forecast Probabilities  
Uncertainties

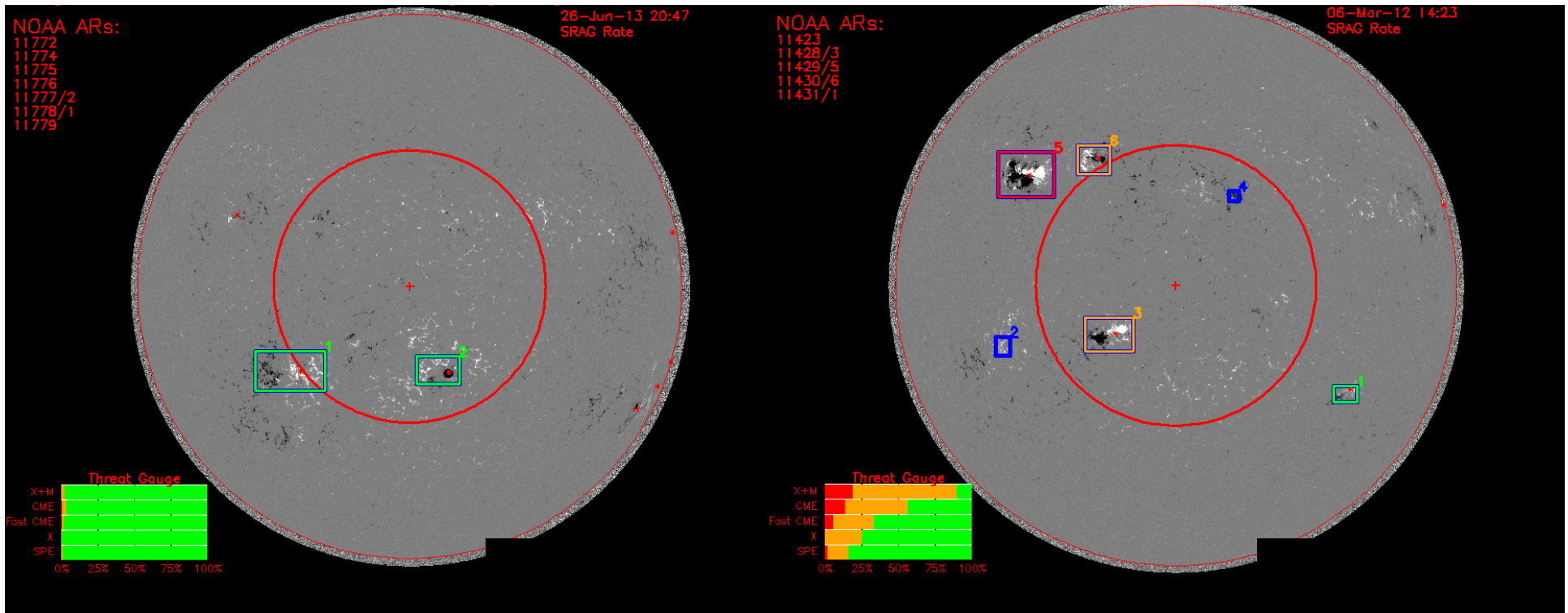
| 24 Hour Event Rate |        |        |        |        | Dist  |
|--------------------|--------|--------|--------|--------|-------|
| M&X                | CME    | FCME   | X      | SPE    | (deg) |
| 0.020              | 0.020  | 0.009  | 0.002  | 0.003  | 27    |
| 0.700              | 0.400  | 0.200  | 0.100  | 0.080  | 44!   |
| 0.020              | 0.030  | 0.010  | 0.004  | 0.005  | 32!   |
| 0.000              | 0.001  | 0.001  | 0.000  | 0.000  | 45!   |
| 0.800              | 0.400  | 0.200  | 0.100  | 0.090  |       |
| 2.7x               | 2.1x   | 2.2x   | 3.0x   | 2.4x   |       |
| 50.00%             | 70.00% | 80.00% | 90.00% | 92.00% |       |
| 40.00%             | 20.00% | 10.00% | 10.00% | 7.00%  |       |

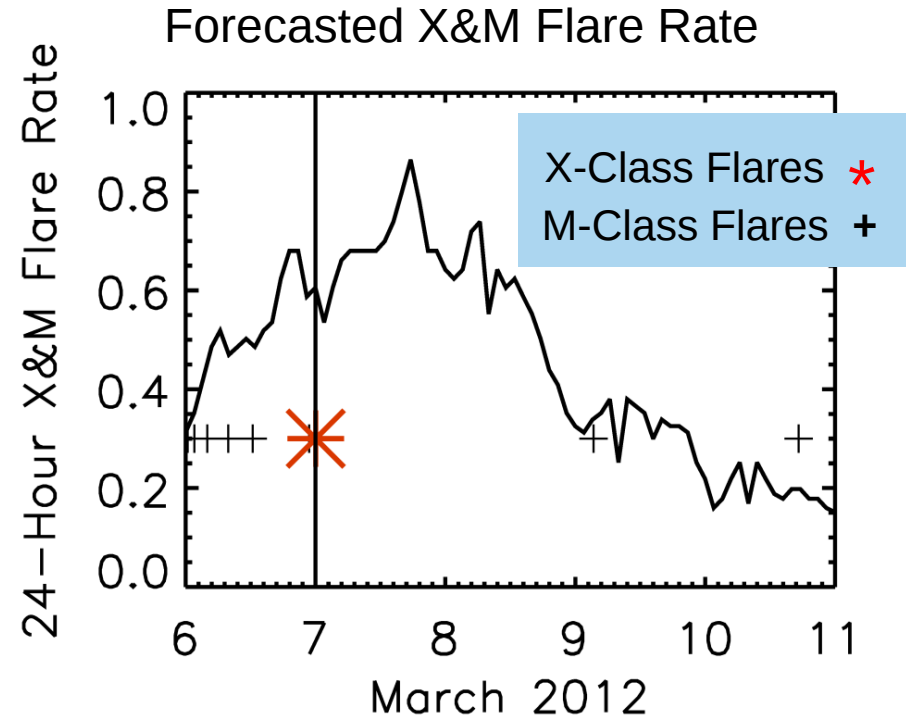
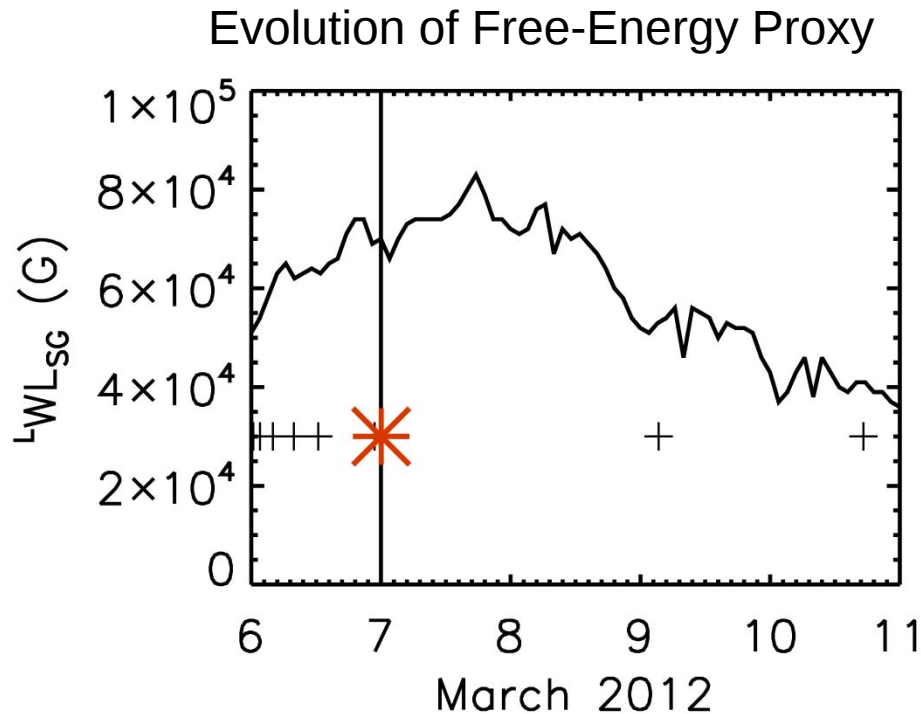


# Comparison of Safe and Not Safe Days

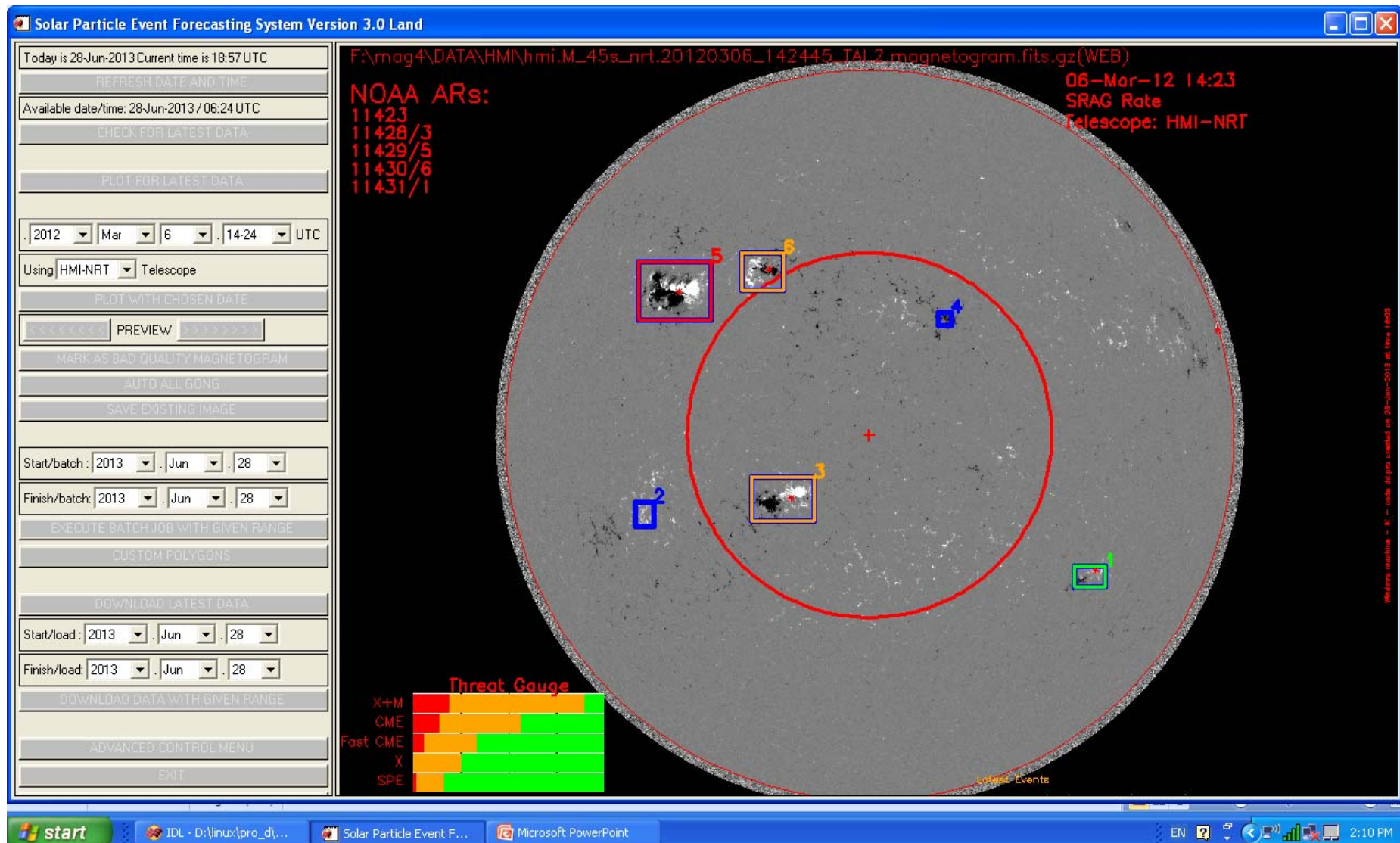
June 26, 2013  
C1, C1.5 flares

March 7, 2012  
X5.4, X1.3, C1.6  
CME 2684, 1825 km/sec,  
Solar Energetic Proton Event reaches  
6530 particle flux unit >10MeV



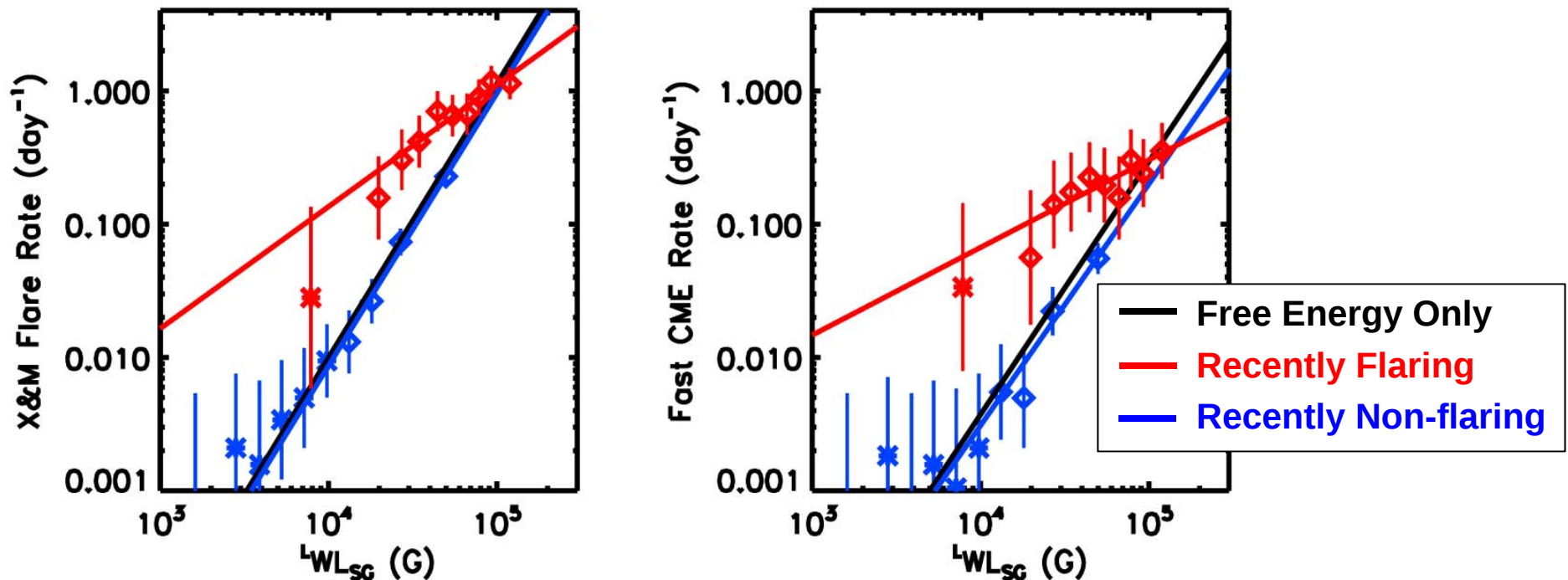


The Free-Energy Proxy evolves on time periods of days,  
and the forecast is on those time scales.





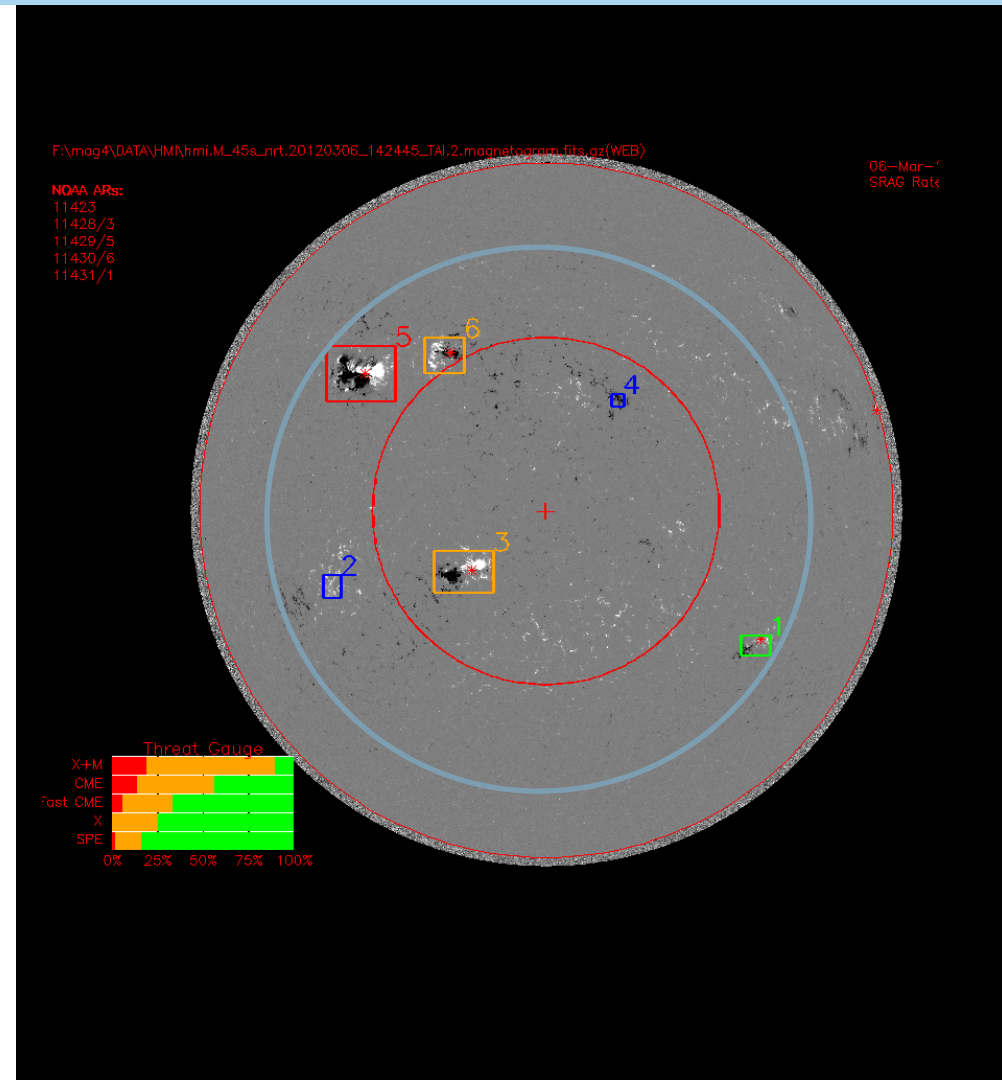
## 1. Recent Flare History (In Progress)



Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

## 2. Vector Magnetograms (In Progress)

- MAG4 presently uses SDO/HMI line-of-sight magnetograms
- Near-real-time Ambiguity-Resolved SDO/HMI vector-magnetograms have recently become available
- We are transitioning to using these new data from SDO
- Implementation just started

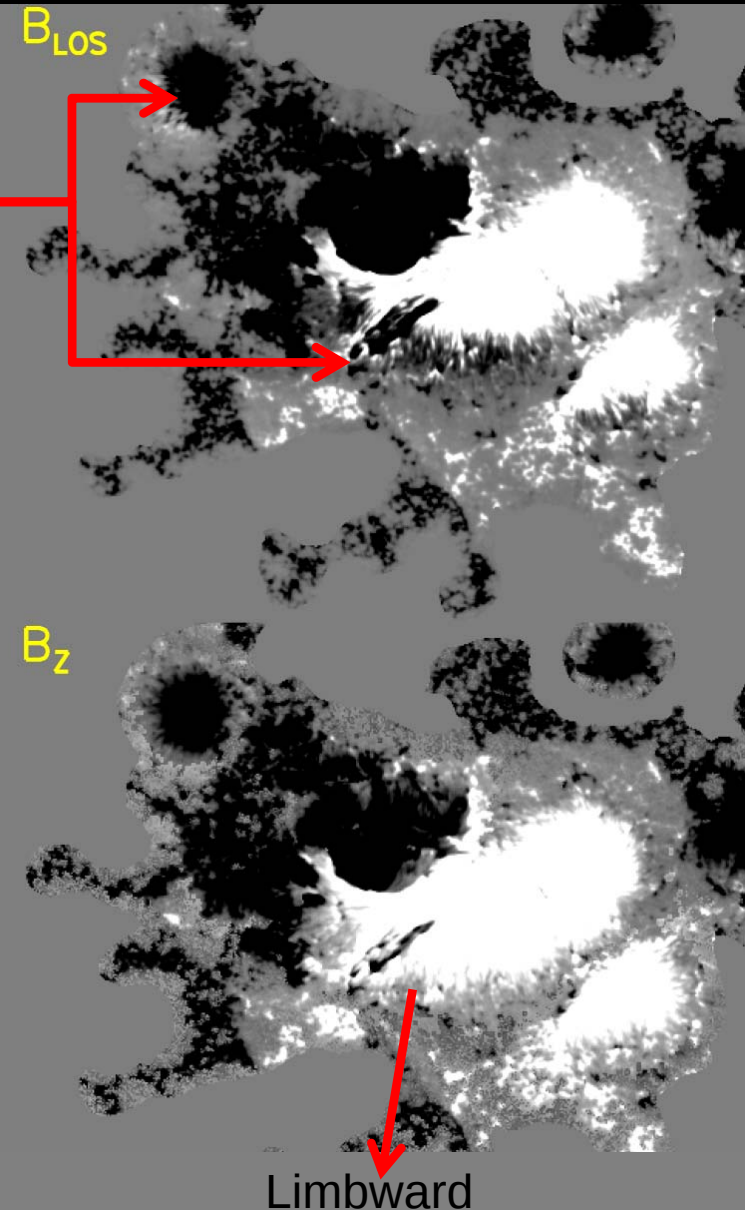
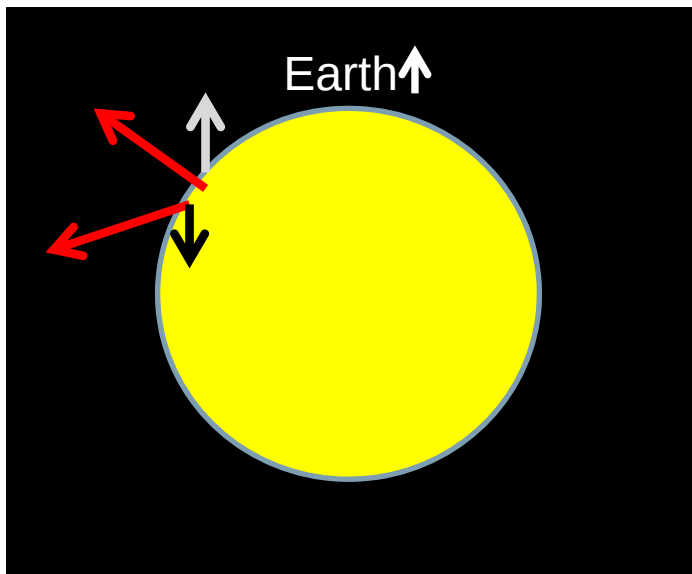


- Both vectors shown in red have positive  $B_z$  (magnetic field out of the sun), but have opposite sign  $B_{LOS}$  and thus a false (unphysical) neutral line in the line-of-sight (LOS) field.

Actual Examples

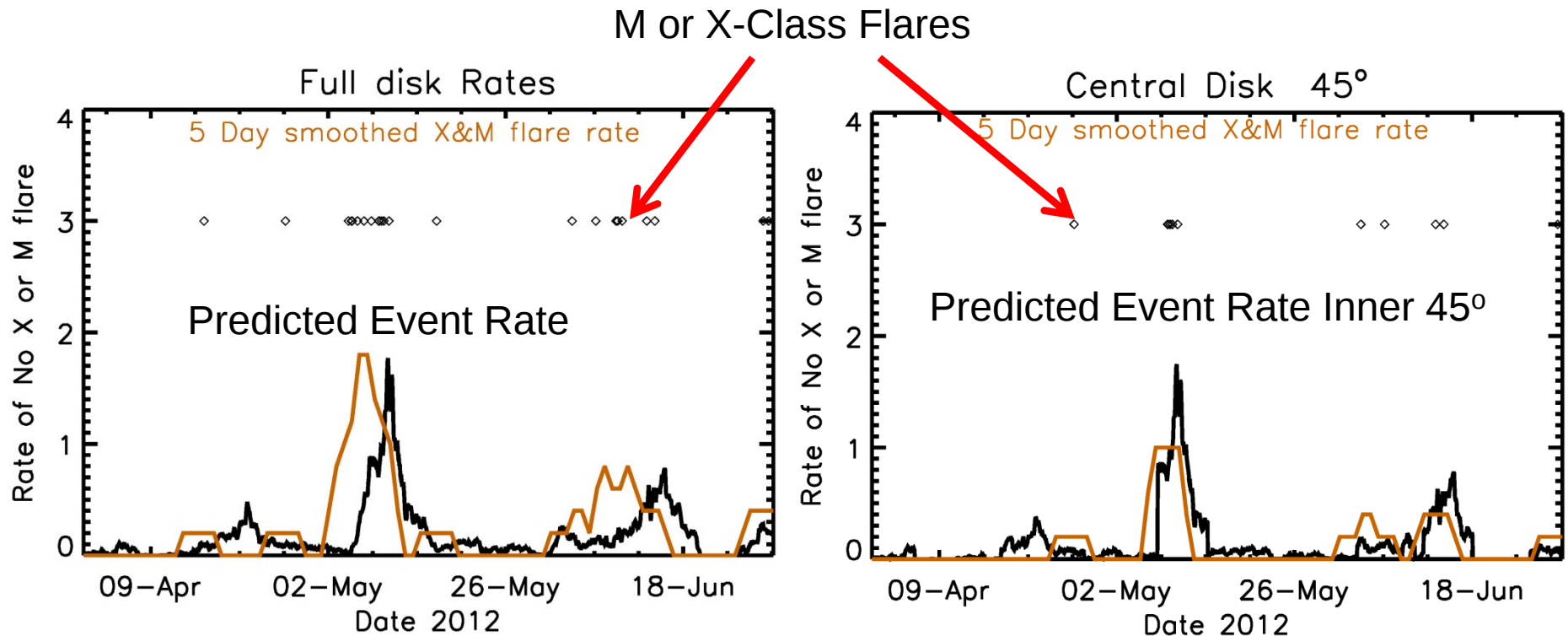
False Neutral Lines occur on limbward sides of sunspots.

Problem fixed by converting from  $B_{LOS}$  and  $B_{Transverse}$  to  $B_z$  and  $B_{Horizontal}$



## 1. Situational Awareness

- During periods when flare-productive active regions cross the disk, the predicted rate and actual rate both increase, providing situational awareness
- The results are best when flares and predicted rates are limited to inner 45 degree circle (Right)



## 2. Skill Metrics

| Truth Table | Actual Yes | Actual No |
|-------------|------------|-----------|
| Predict Yes | YY         | YN        |
| Predict No  | NY         | NN        |

PC Percent Correct  
 POD Probability of Detection  
 FAR False Alarm Rate  
 HSS Heidke Skill Score  
 TSS True Skill Score

| Forecast Method                                                          | YY  | YN  | NY  | NN    | PC          | POD         | FAR         | HSS         | TSS         |
|--------------------------------------------------------------------------|-----|-----|-----|-------|-------------|-------------|-------------|-------------|-------------|
| McIntosh/NOAA                                                            | 259 | 638 | 631 | 18476 | 93.7        | 0.29        | 0.71        | 0.26        | 0.26        |
| Free-Energy Proxy<br><b>Present MAG4</b>                                 | 273 | 284 | 618 | 18830 | 95.5        | 0.31        | 0.50        | 0.35        | 0.47        |
| Free-energy proxy and<br>previous flare activity<br><b>Upgraded MAG4</b> | 340 | 317 | 551 | 18797 | <b>95.7</b> | <b>0.38</b> | <b>0.48</b> | <b>0.42</b> | <b>0.49</b> |
| Best                                                                     | 890 | 0   | 0   | 19114 | 100         | 1           | 0           | 1           | 1           |



- Customizing MAG4 to AFWA needs
- Further development of MAG4
  - R2O: use time series, Heliosphere propagation of CME, Helioseimology, Improve forecasts as with flare history
  - Operational Tool: Robustness, usability, interface
- Independent Verification Tests



# Backup Slides



## 2. Skill Metrics Equations

|             | Actual Yes | Actual No |
|-------------|------------|-----------|
| Predict Yes | YY         | YN        |
| Predict No  | NY         | NN        |

### Metric Equations

|                          |                                                                                   |
|--------------------------|-----------------------------------------------------------------------------------|
| Percent Correct          | $PC = (YY + NN) / (YY + YN + NY + YY)$                                            |
| Probability of Detection | $POD = YY / (YY + NY)$                                                            |
| False Alarm Rate         | $FAR = YN / (YY + YN)$                                                            |
| Heidke Skill Score       | $HSS = 2 * (YY * NN - YN * NY) / [(YY + NY) * (NY + NN) + (YY + YN) * (YN + NN)]$ |
| True Skill Score         | $TSS = (YY * NN - NY * YN) / ((YY + NY) * (YN + NN))$                             |

Flares occur when high free-energy proxy active regions crossing disk.

